ARTICLES

MORPHOLOGICAL TYPIFICATIONS OF SLOVENIA'S SURFACE USING GLOBAL CLASSIFICATION METHODS

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ABSTRACT
Morphological typifications of Slovenia's surface using global classification methods
Morphology is often the most important factor in distinguishing landscapes and is an important element in geographical classifications, typifications, and regionalizations. Therefore, morphological divisions of the surface have a long tradition in Slovenia and abroad. The development of geographic information systems has significantly increased the number of methods and indicators used for determining, analyzing, and classifying morphological units at various size levels. In terms of spatial combinations, one distinguishes between continuous and discontinuous surface classifications, and between global and regional surface classifications in terms of the values and value limits of indicators. This article presents examples of foreign methods of global surface classification of Slovenia and compares them to the established Slovenian typification of Slovenia's surface.

KEY WORDS
geomorphology, relief, surface, continuous and discontinuous surface classification method, global and regional surface classification method, digital elevation model, geographic information system, Slovenia

IZVLEČEK
Morfološke tipizacije površja Slovenije z globalnimi metodami
Oblikovanost površja je pogosto najpomembnejši dejavnik razlikovanja med pokrajinami in pomembna prvina pri geografskih klasifikacijah, tipizacijah in regionalizacijah, zato imajo morfološke delitve površja v tujini in pri nas že dolgo tradicijo. Z razvojem geografskih informacijskih sistemov se je močno povečalo število metod in kazalnikov za določanje, analizo in razvrščanje enot oblikovanosti površja na različnih velikostnih ravneh. Glede na prostorsko združevanje lahko ločimo zvezne in nezvezne delitve površja, glede na vrednosti in meje vrednosti kazalnikov pa globalne in regionalne delitve površja. V prispevku predstavljamo primere tujih metod globalne delitve površja Slovenije in jih primerjamo z uveljavljeno slovensko tipizacijo površja Slovenije.

KLJUČNE BESEDE
geomorfologija, relief, površje, metoda zvezne in nezvezne delitve površja, metoda globalne in regionalne delitve površja, digitalni model višin, geografski informacijski sistem, Slovenija

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1 Introduction

Morphology is often the most important factor in distinguishing between landscapes and an important element in geographical classifications, typifications, and regionalizations. Therefore, morphological classifications of the surface have a long tradition in Slovenia and abroad. The development of geographic information systems has significantly increased the number of methods and indicators used for determining, analyzing, and classifying morphological units at various size levels.

The former tedious and time-consuming landform classifications based on maps have been replaced by faster and more accurate classifications using computer-supported geographic information systems. These types of classifications are more objective, even though the selection of classification elements and their classes remain subjective. Iwahashi and Pike (2006) prepared an overview of 12 landform classifications that have been published in recent years and all of them were developed electronically.

Slovenia has an extremely varied relief and can thus serve as a good indicator of the effectiveness or suitability of individual methods and indicators used in landform classification.

2 Global, non-global, continuous, and discontinuous landform classifications

In terms of spatial combinations, one distinguishes between continuous and discontinuous landform classifications, and between global and regional surface classifications in terms of the values and value limits of indicators.

Landform classification may be continuous or discontinuous. Classification and typification may be either continuous or discontinuous, but it is more common for classification to be continuous and typification discontinuous; regionalization is always discontinuous.

In discontinuous landform classification, individual parts of the surface are combined into areas with the same or similar values of selected relief indicators and clear borders with adjacent areas with different values of selected relief indicators. These areas can be referred to as units. Areas with the same or similar values of relief indicators may appear several times in the landscape studied, but they are separated from one another by areas with different values of relief indicators.

In continuous landform classification, individual parts of the surface are classified only based on the values of selected relief indicators, regardless of their spatial position. These non-spatial units are most commonly referred to as classes. Parts of the surface are thus not necessarily connected or do not touch one another, and they can appear anywhere in the landscape studied.

Discontinuous classification is more qualitative, is based on expert knowledge, and has greater applied value; however, it is more subjective. Continuous classification is more quantitative and objective, and has greater analytical value. Continuous landform classification is often only the first stage of discontinuous classification – or, in other words: discontinuous classification is usually an improved continuous landform classification.

In older landform classifications used in Slovenia and elsewhere, discontinuous classifications predominated; however, after the introduction of computers and geographic information systems, continuous classifications and combinations of continuous and discontinuous classifications prevailed.

If a landform classification uses the same values and value limits of selected relief indicators as are used for the entire world, this is referred to as the global landform classification method. If their values and value limits are adjusted to individual areas, this is referred to as the regional landform classification method.

The advantages of the global classification method is that it makes it possible to compare all parts of the world and the advantage of the regional classification method is that internal differences can be shown even in those parts of the world that would remain completely unclassified under the global classification method; this can be achieved by adjusting the values and value limits of relief indicators to *de-facto* conditions in the selected landscape.

In Slovenian and international classifications, typifications, and regionalizations, the global landform classification methods or adjusted global classification methods prevail; the use of the regional landform classification method, which in itself contains elements of adaptation to various landscapes, is very rare. Adjusted global landform classification methods thus represent a type of intermediate solution between global and regional landform classifications.

3 Hammond

One of the first and best-known morphological typifications was developed by the American geographer Edwin H. Hammond, who classified the land-surface forms of the U.S. in greater detail (Hammond 1964). Later on, his method was reused several times using the geographic information system and the digital elevation model (Dikau, Brabb, and Mark 1991; Brabyn 1998; Gallant, Douglas, and Hoffer 2005).

Hammond used a square cell with a baseline of 6 miles (approximately 9.65 km and an area of 93.12 km^2) as the basic surface unit for calculating relief elements; this may seem enormous, but in the U.S. context this does not even account for 0.001% of its entire territory. The cells followed one another without overlapping. Using 1 : 250,000 maps, he defined the following three elements for each cell: slope, local relief, and profile type. He labeled each element with an agreed-upon sign and used their combinations to determine the land-surface form units.

The first element in Hammond's classification is slope. For each cell, he calculated what share of its area has a slope below 8% (approximately 4.57°). He labeled this element with capital letters:
- A: > 80% of area gently sloping,
- B: 50–80% of area gently sloping,
- C: 20–50% of area gently sloping,
- D: < 20% of area gently sloping.

The second element in Hammond's classification is local relief. He defined the maximum and minimum elevation and their difference for each cell. He labeled this element with numerals:
- 1: 0–30 m,
- 2: 30–90 m,
- 3: 90–150 m,
- 4: 150–300 m,
- 5: 300–900 m,
- 6: 900–1,500 m.

The third element in Hammond's classification is profile type. For each cell he defined the percentage of gently inclined surface that lies below or above the average local relief of the cell. He labeled this element with lower-case letters:
- a: > 75% of gentle slope is in lowland,
- b: 50–75% of gentle slope is in lowland,
- c: 50–75% of gentle slope is on upland,
- d: > 75% of gentle slope is on upland.

Hammond combined these elements to define the land-surface forms. He drew them onto a large color map at a scale of 1 : 5,000,000. However, he did not present the results of his classification in square form, but with the land-form boundaries that he set subjectively by following the edges of flat plains, tablelands, hills, and similar major relief forms. Because of this the map is slightly generalized, but more synoptic.

To define the landform units, Hammond used three elements with four (slope), six (local relief), and another four (profile type) classes; this theoretically makes up 96 combinations or 96 possible landform units. However, he actually only chose 21 units, which he combined into five groups (plains, tablelands, plains with hills or mountains, open hills and mountains, and hills and mountains).

Only 13 of his 21 landform units (morphological types) appear in Slovenia (Table 1, Figure 1).

Table 1: Morphological types of Slovenia according to Hammond.

	Unit	km^2	%
1	Flat plains	99.83	0.49
2	Smooth plains	93.40	0.46
3	Tablelands with moderate relief	1.93	0.01
4	Plains with hills	609.21	3.01
5	Plains with high hills	1,102.06	5.44
6	Plains with low mountains	1,371.04	6.76
7	Open hills	141.44	0.70
8	Open high hills	819.23	4.04
9	Open low mountains	3,990.24	19.68
10	Open high mountains	411.04	2.03
11	High hills	147.23	0.73
12	Low mountains	6,003.36	29.61
13	High mountains	5,482.92	27.05

4 Meybeck, Green and Vörösmarty

The classification by Meybeck, Green, and Vörösmarty (2001) is the simplest of all the ones presented because the authors only used two classification elements: relief roughness and mean elevation. They used the global digital elevation model GTOPO30 with 30 arc seconds grid resolution, which corresponds to approximately 1 km.

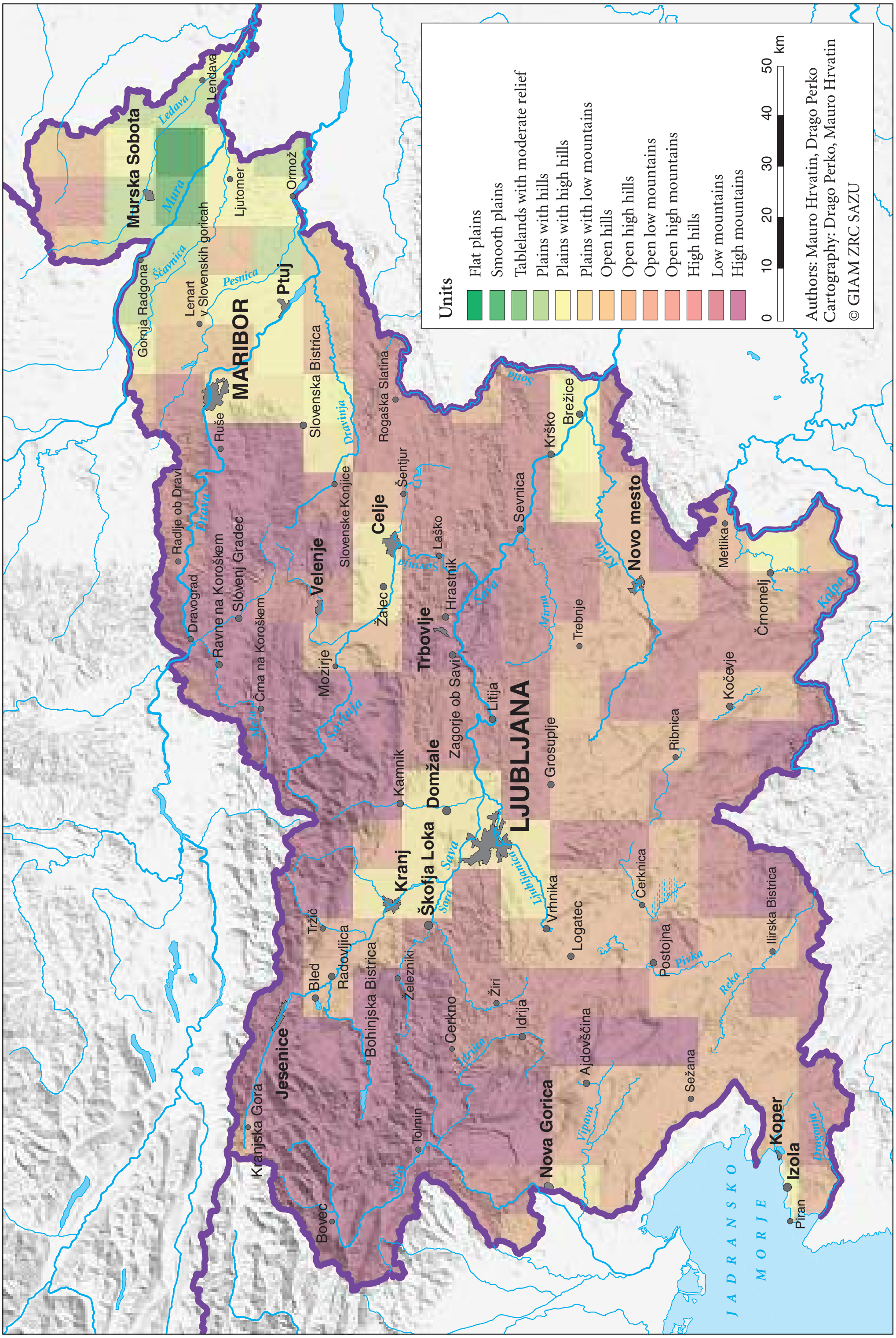
The first element used in the classification by Meybeck, Green, and Vörösmarty is relief roughness. They defined the maximum and minimum elevation for each cell and divided their difference by the cell's baseline length. The unit of relief roughness calculated this way is 1 m/km or ‰. They divided the values estimated into seven classes:

- 1: < 5‰,
- 2: 5–10‰,
- 3: 10–20‰,
- 4: 20–40‰,
- 5: 40–80‰,
- 6: 80–160‰,
- 7: > 160‰.

The second classification element is the average elevation. The values estimated were divided into eight classes:

- 1: 0–200 m,
- 2: 200–500 m,
- 3: 500–1,000 m,
- 4: 1,000–2,000 m,
- 5: 2,000–3,000 m,
- 6: 3,000–4,000 m,
- 7: 4,000–5,000 m,
- 8: 5,000–6,000 m.

Figure 1: Morphological typification of Slovenia according to Hammond. ➤


Units
Flat plains
Smooth plains
Tablelands with moderate relief
Plains with hills
Plains with high hills
Plains with low mountains
Open hills
Open high hills
Open low mountains
Open high mountains
High hills
Low mountains
High mountains
0 10 20 30 40 50 km
Authors: Mauro Hrvatin, Drago Perko
Cartography: Drago Perko, Mauro Hrvatin
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LJUBLJANA
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Celje
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Koper
Novo mesto
Murska Sobota
Ptuj
Velenje
Nova Gorica
Jesenice
JADRANSKO MORJE

Meybeck, Green, and Vörösmarty combined these elements to define 15 landform units, of which 13 also appear in Slovenia. The typification of Slovenia's surface, which was performed as part of the typification of the surface of the entire world following the methodology developed by Meybeck, Green, and Vörösmarty, was taken from the website of the Institute for Environment and Sustainability, which is part of the European Commission Joint Research Centre (Internet 1).

Table 2: Morphological types of Slovenia according to Meybeck, Green, and Vörösmarty.

	Unit	km^2	%
1	Plains	1,063.04	5.24
2	Mid Altitude Plains	1,723.99	8.50
3	High Altitude Plains	145.31	0.72
4	Lowlands	580.66	2.86
5	Rugged Lowlands	66.96	0.33
6	Very Low Plateaus	5,514.21	27.20
7	Low Plateaus	2,554.05	12.60
8	Mid Altitude Plateaus	305.83	1.51
9	High Altitude Plateaus	10.15	0.05
10	Hills	1,904.12	9.39
11	Low Altitude Mountains	4,529.24	22.34
12	Mid Altitude Mountains	1,815.29	8.95
13	High Altitude Mountains	60.10	0.30

5 Iwahashi and Pike

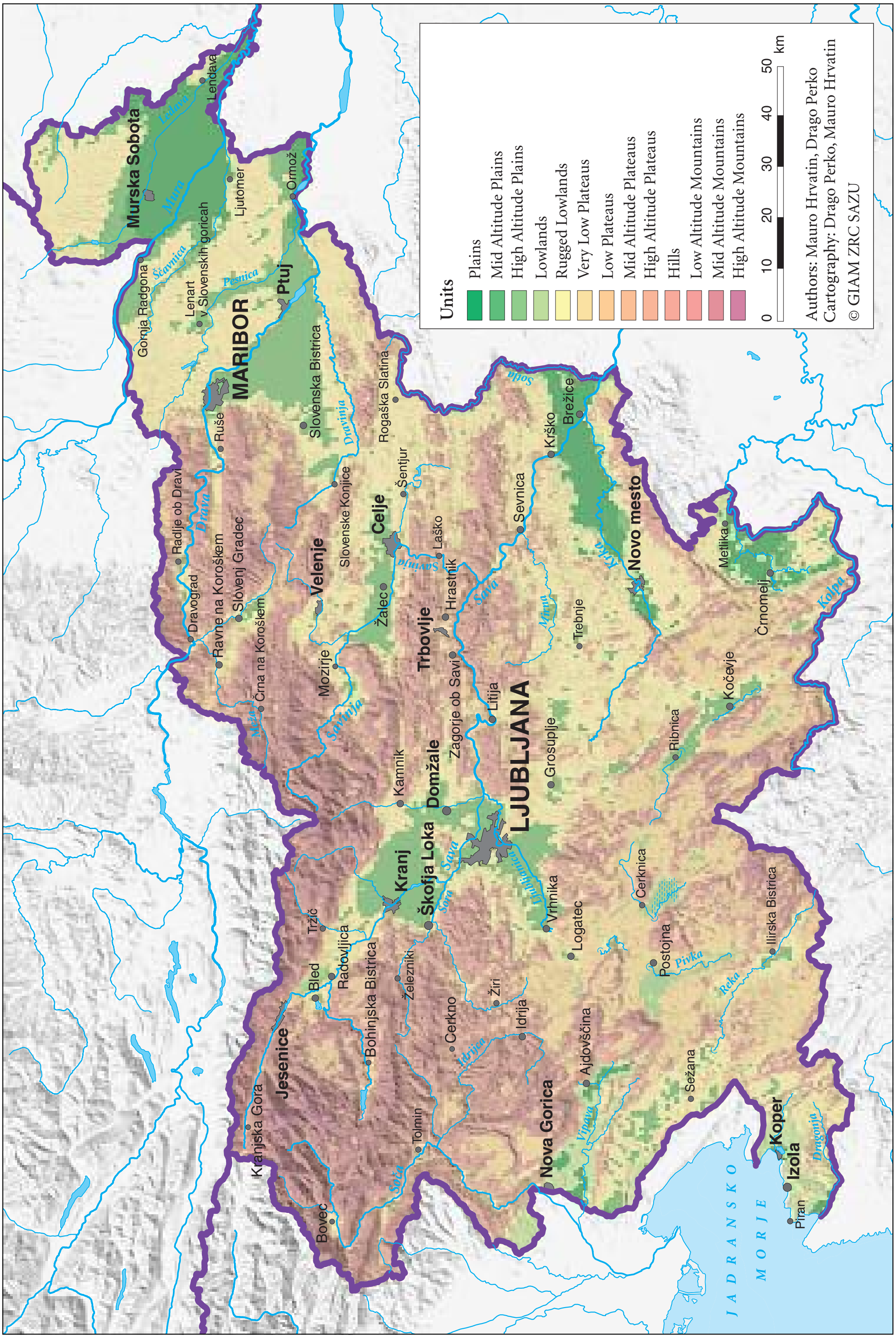
Iwahashi and Pike (2007) developed their landform classification in three areas of various size using three different digital elevation models. Their landform classification of a part of Hokkaido was based on a 55-meter digital elevation model, their classification of Japan was based on a 270-meter digital elevation model, and their classification of the world was based on a 1,000-meter digital elevation model.

They used the same criteria in all of their classifications:

- Slope gradient,
- Local convexity,
- Surface texture.

They calculated slope gradient with ArcGIS, which uses Horn's algorithm (1981). They determined local convexity using the highly permeable Laplacian filter for detecting edges, which is similar to the mathematical operation of the second derivative. This filter enhances the edges in all directions and thus the basic features of landforms such as the bottoms of valleys and the peaks of ridges. They determined the surface texture so that they first calculated the median of every cell using a 9-cell moving window (3×3 cells). Then they subtracted the layer with the median values from the original digital elevation model and thus gained a layer in which the peaks of ridges and the bottoms of valleys were the most pronounced. From the geomorphological viewpoint, this layer could be named the map of density of valleys and ridges. At the same time, this layer shows the terrain or the surface texture. In further developing the surface texture indicator, they took into account all of the positive and negative cells and ascribed them the value 1; all the other cells retained the value 0. Then they used a round

Figure 2: Morphological typification of Slovenia according to Meybeck, Green, and Vörösmarty. ➤


Units
Plains
Mid Altitude Plains
High Altitude Plains
Lowlands
Rugged Lowlands
Very Low Plateaus
Low Plateaus
Mid Altitude Plateaus
High Altitude Plateaus
Hills
Low Altitude Mountains
Mid Altitude Mountains
High Altitude Mountains
0 10 20 30 40 50 km
Authors: Mauro Hrvatin, Drago Perko
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Ravne na Koroškem
Slovenj Gradec
Črna na Koroškem
Velenje
Slovenske Konjice
Celje
Šentjur
Laško
Žalec
Hrastnik
Trbovlje
Mozirje
Zagorje ob Savi
Litija
Sevnica
Krško
Brežice
Novo mesto
Metlika
Črnomelj
Trebnje
Kočevje
Ribnica
Grosuplje
LJUBLJANA
Kamnik
Domžale
Kranj
Škofja Loka
Tržič
Bled
Radovljica
Jesenice
Kranjska Gora
Bohinjska Bistrica
Železniki
Cerkno
Žiri
Idrija
Vrhnika
Logatec
Cerknica
Postojna
Ilirska Bistrica
Ajdovščina
Nova Gorica
Tolmin
Bovec
Sežana
Koper
Izola
Piran
JADRANSKO MORJE
Mura
Ledava
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Dravinja
Savinja
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Sotla
Krka
Kolpa
Mirna
Meža
Ljubljanica
Pivka
Reka
Idrijca
Soča
Vipava
Dragonja

moving window with a diameter of 10 cells to determine the frequency of the terrain. This data finaly enabled them to calculate the percentage of terrain occurrence for each cell by dividing the frequency of occurrence by the area of the round moving window.

Iwahashi and Pike connected the prepared classification layers (slope gradient, local convexity, and surface texture) using the nested-means classification procedure, which was introduced to geographical research and classification by Scripter (1970) and makes it possible to divide the surface into 8, 12, or 16 classes.

This procedure is especially recommended for dividing unevenly or asymmetrically classified data such as data on the elevation and slope gradient, in which greater values are increasingly rarer.

The typification of Slovenia's surface made following Iwahashi's and Pike's methodology as part of the typification of the entire world's surface was based on the website of the Geospatial Information Authority of Japan (Internet 2).

Of the 16 landform units defined by Iwahashi and Pike in their classification of the world surface, 13 appear in Slovenia (Table 3, Figure 3).

Table 3: Morphological types of Slovenia according to Iwahashi and Pike.

	Unit	km^2	%
1	Gentle surface with low convexity and coarse texture	190.03	0.94
2	Gentle surface with low convexity and fine texture	574.63	2.83
3	Gentle surface with high convexity and fine texture	59.83	0.30
4	Moderately gentle surface with low convexity and coarse texture	44.13	0.22
5	Moderately gentle surface with low convexity and fine texture	925.44	4.56
6	Moderately gentle surface with high convexity and fine texture	245.37	1.21
7	Moderately steep surface with low convexity and coarse texture	80.25	0.40
8	Moderately steep surface with low convexity and fine texture	3,060.27	15.10
9	Moderately steep surface with high convexity and fine texture	1,720.62	8.49
10	Steep surface with low convexity and coarse texture	95.61	0.47
11	Steep surface with low convexity and fine texture	5,599.23	27.62
12	Steep surface with high convexity and coarse texture	10.05	0.05
13	Steep surface with high convexity and fine texture	7,667.47	37.82

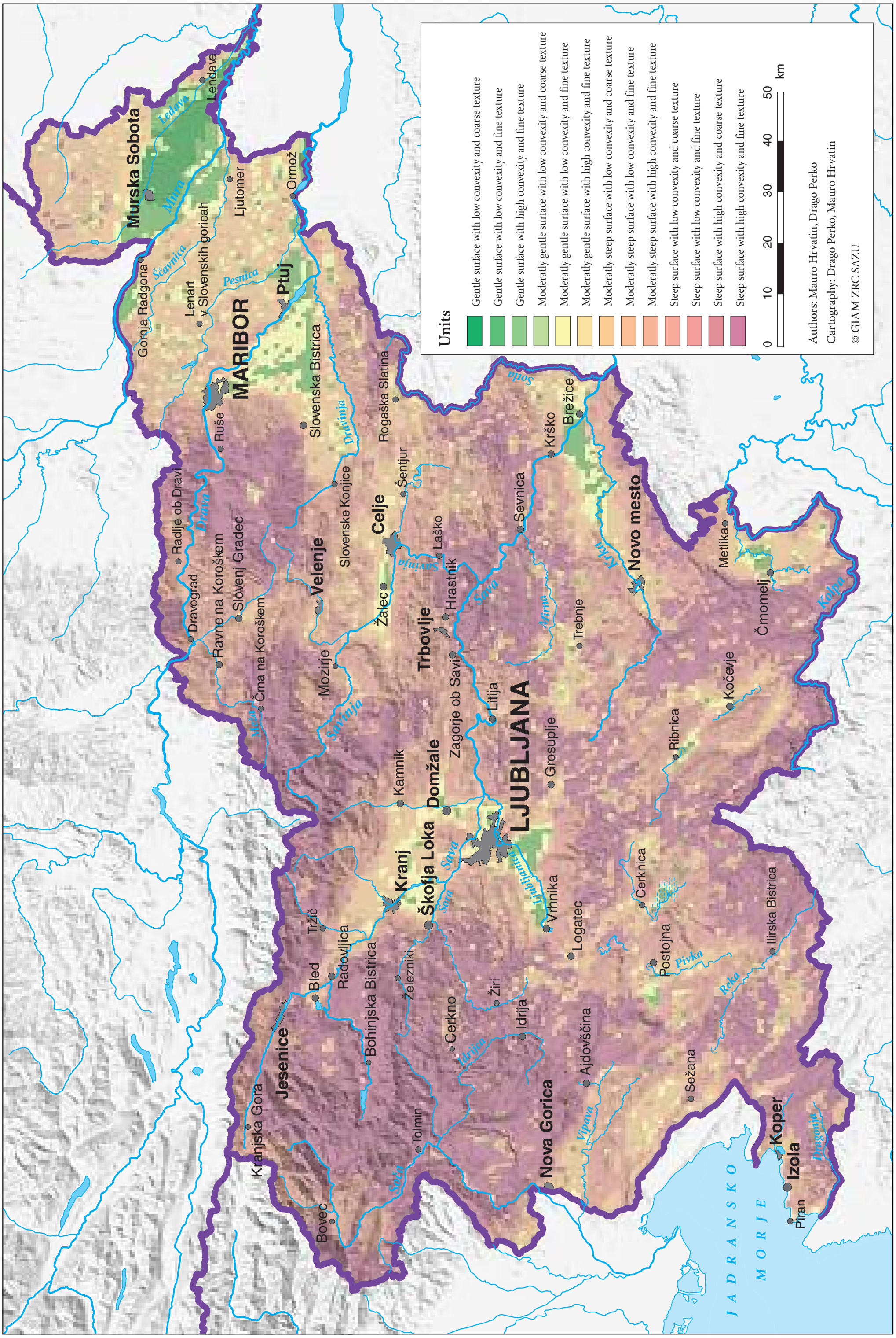
6 Perko

The first computerized relief typification in Slovenia was created by Drago Perko, who initially divided Slovenian territory into eight landform units (Perko 1992; 2001; 2007), and later on into seven (Table 4, Figure 4).

This classification is based on spatial variability in elevation and slope. For each square cell of a 100-meter digital elevation model, Perko took into account its eight neighboring cells (a moving window measuring 9 ha or 3 × 3 cells) to first calculate the elevation variation and the slope variation coefficient; following this, he used both variation coefficients to calculate their geometric mean, which he called the relief coefficient (Perko 2001). By generalizing the relief coefficient, he defined the landform units. He manually adjusted the final borders between these units to the natural borders in the landscape (rivers, plateau edges, etc.).

Later he determined the variability of Slovenia's relief (Perko 2007) using a new version of the relief coefficient, which he calculated as a geometric mean of the slope variation coefficient and the aspect

Figure 3: Morphological typification of Slovenia according to Iwahashi and Pike. ➤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Gentle surface with low convexity and fine texture
Gentle surface with high convexity and fine texture
Moderately gentle surface with low convexity and coarse texture
Moderately gentle surface with low convexity and fine texture
Moderately gentle surface with high convexity and fine texture
Moderately steep surface with low convexity and coarse texture
Moderately steep surface with low convexity and fine texture
Moderately steep surface with high convexity and fine texture
Steep surface with low convexity and coarse texture
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Steep surface with high convexity and coarse texture
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Sevnica
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Brežice
Novo mesto
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Črnomelj
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variation coefficient of each square cell of the 25-meter digital elevation model and its 120 neighbors (a moving window measuring 75,625 ha or 11 × 11 cells).

Table 4: Morphological types of Slovenia according to Perko.

	Unit	km^2	%
1	Plains	1,918.31	9.46
2	Rough Plains	1,195.38	5.90
3	Low Hills	4,842.91	23.89
4	Rough Low Hills	2,645.48	13.05
5	High Hills	6,686.63	32.98
6	Rough High Hills	1,028.94	5.08
7	Mountains	1,955.29	9.64

7 Conclusion

Various surface classifications are more or less successful in dividing Slovenia's surface. The majority show Slovenia as a hilly or even mountainous country with a diverse relief. Some areas are placed in classes that deviate considerably from the actual conditions. The classification criteria have obviously been adjusted to areas with less diverse relief, such as the North European Plain, the West Siberian Plain, and the Tibetan Plateau. However, with appropriate modification of the classification criteria (Perko and Hrvatin 2009) the same classifications yield significantly better results even for countries with such a diverse relief as Slovenia.

Hammond's method proved to be of relatively good quality in classifying the surface of the United States. However, for Slovenia, where the morphological features of the surface change rapidly in space, this method is insufficiently accurate. Thus a number of Slovenian landscapes are classified in units that do not show their actual morphological features because, due to the size of the basic square cell, the morphological features of their neighboring landscapes are also taken into account. The original basic cell with an area of nearly 100 km^2 is significantly too large to determine all three of Hammond's elements for Slovenia.

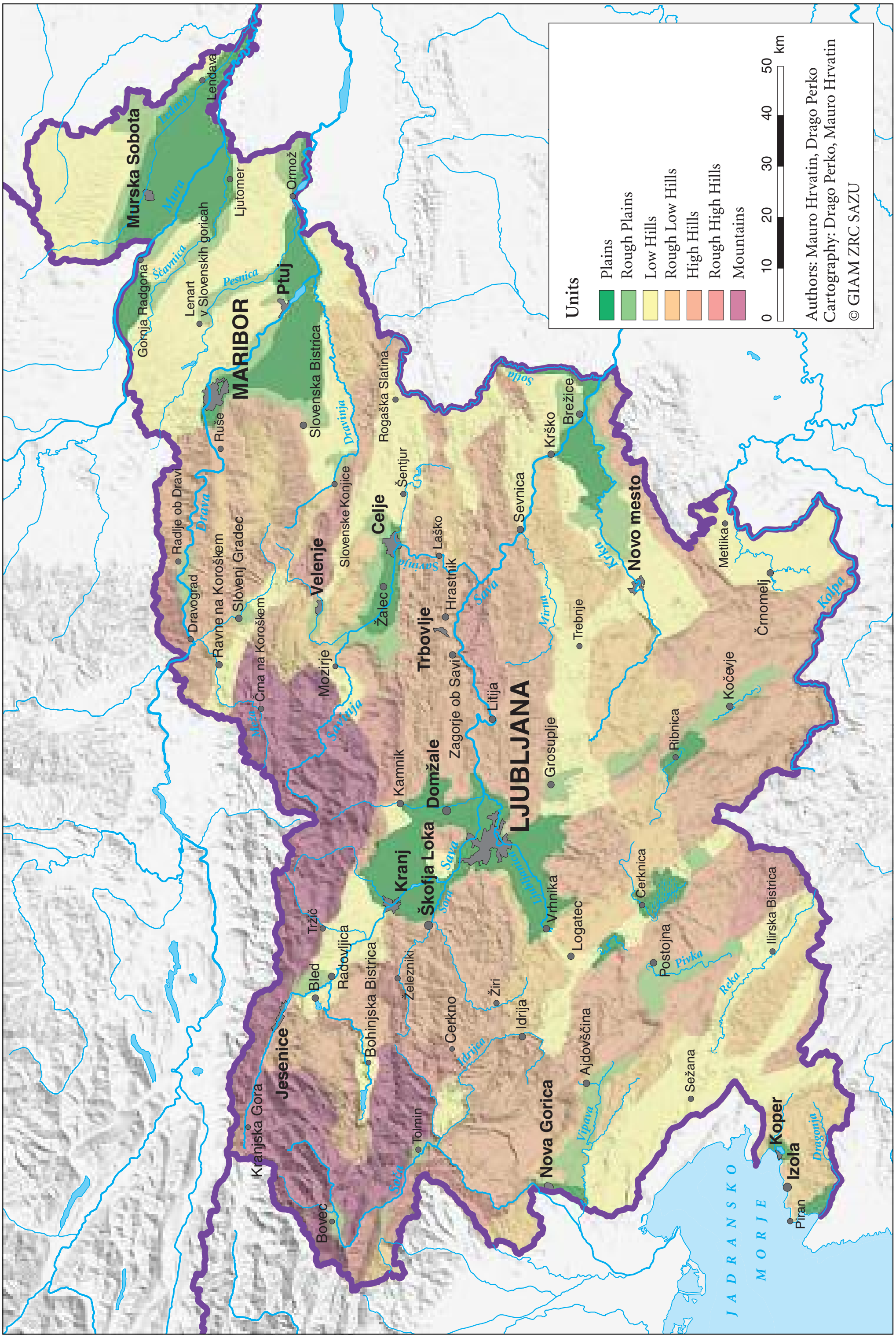
The results of **Meybeck, Green, and Vörösmarty's method** are the closest to our idea of Slovenia's landforms. Among all three foreign methods selected, it is the only one that does not require major adjustments. However, as in practically all computerized surface classifications, individual relief units are spatially too fragmented.

Of the 16 classes in the original classification of the entire world's surface following **Iwahashi and Pike's method**, 13 classes appear in Slovenia. The percentage of the surface covered by individual classes is very uneven because nearly nine-tenths of Slovenian territory is classified under only four classes. The weaknesses noticed in this classification include the excessive similarity between the second and third classification criteria (the percentage of local convexity and surface texture), which consequently partly duplicate each other.

It is interesting that all three selected foreign classifications are statistically more correlated with that of Perko (correlation coefficients between 0.345 and 0.446) than with one another (correlation coefficients between 0.270 and 0.306). The classification by Meybeck, Green, and Vörösmarty statistically correlates the best with Perko's classification (correlation coefficient of 0.446) (Table 5).

By comparing the units in Perko's classification or typification with the units used by Hammond, by Meybeck, Green, and Vörösmarty, and by Iwahashi and Pike, it can be seen how the use of the glob-

Figure 4: Morphological typification of Slovenia according to Perko. ➤


Units
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Rough Plains
Low Hills
Rough Low Hills
High Hills
Rough High Hills
Mountains
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Domžale
Škofja Loka
Izola
J A D R A N S K O M O R J E

al classification methods can create a poor or completely wrong picture in smaller areas with diverse relief.

Table 5: Correlation coefficients between the morphological typifications of Slovenia.

	Hammond's classification	Meybeck, Green, and Vörösmarty's classification	Iwahashi and Pike's classification	Perko's classification
Hammond's classification	1.000	0.306	0.296	0.413
Meybeck, Green, and Vörösmarty's classification	0.306	1.000	0.270	0.446
Iwahashi and Pike's classification	0.296	0.270	1.000	0.345
Perko's classification	0.413	0.446	0.345	1.000

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